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SCATTERING AND DEPOLARIZATION BY ROUGH TERRAIN AND SEA

A UNIFIED FULL WAVE APPROACH

FINAL REPORT

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PRINCIPAL INVESTIGATOR

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During the period of this contract (July 1, 1987-June 30, 1990) the principal investigator presented twenty-four (24) papers at scientific/technical meetings (see Item 7.1a) and five (5) additional papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item 7.1b). Twenty-six (26) papers were submitted to Journal Editors for review (see Item (7.2)) and eighteen (18) were accepted for publication (see Item (7.3)). Twenty-two (22) papers were published in journals and conference proceedings (see Item (7.4)) and reprints of these papers have been submitted along with the six (6) semiannual progress reports. One (1) Interim Report and three (3) M.S. Theses have been completed during this reporting period (see Item (7.5)), copies were submitted with the Progress Reports) Two (2) Ph.D. Dissertations based on the research conducted under this contract will be completed by the end of next year (see Section 4). Details of the research results are provided in the reprints submitted with the Semiannual Progress Reports and the preprints of manuscripts sent directly to the Project Monitor. (continued on back)

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The principal results are summarized here.

1. Two separate approaches have been developed to account for multiple scatter from rough surfaces. This first approach involves a second order iterative solution. The second approach involves the numerical solution of the generalized telegraphists' equations for the scattered wave amplitudes.

2. In the high frequency limit shadowing is accounted for by limiting the angles of incidence and scatter to less than 90^θ. This is referred to as self shadow. In addition shadowing is due to obstruction by distant topographical features. In the low frequency limit it is only necessary to account for self shadow.

3. The random rough surfaces are usually characterized by Gaussian surface height and slope probability density functions. In this work a broad family of non Gaussian probability density functions are considered. These are based on the gamma functions of order K. Methods based on the examination of the tilt modulation of the scattering cross sections are suggested to remotely determine the appropriate statistical characterization of the surface under observation.

4. To determine the rough surface cross sections, the random rough surfaces need to be characterized by their joint characteristic functions. Both Gaussian and non Gaussian spectral density functions have been considered in this work.

5. The medium below the rough interface is characterized by its complex permittivity and permeability. Thus conduction currents and displacement currents are accounted for in the analysis.

6. To make the problem of evaluating the scattering cross sections of random rough surfaces more tractable, it is usually assumed that the rough surface heights and slopes are statistically uncorrelated. In an attempt to examine the validity of the assumption random rough surfaces are characterized by four dimensional Gaussian joint probability density functions for the surface heights and slopes at two distinct points.

7. The observed phenomena of enhanced backscatter from very rough surfaces (including particles with rough surfaces) has been examined in some detail. It is shown that at oblique angles ($\theta_0 > 20^0$) single scatter is the principal contributor to the observed enhanced backscatter, while for near normal incidence the singly scattered and multiply scattered contributions to the field add constructively or destructively about the backscatter direction.

8. Investigations were conducted to determine the scattering cross sections of rough surfaces that are modified by the presence of oil slicks, ship wakes, swells and other anisotropic surface features. The motivation for this work is remote detection of these special features of the rough surface.

9. For the vector problem of electromagnetic scattering by two dimensional rough surfaces, the excitations considered are in general elliptically polarized waves. The results can be applied directly to polarimetric remote sensing.

10. As in the past several attempts have been made to obtain experimental validation of the numerical/analytical results based on the full wave approach. To this end the full wave unified and two scale solutions have been used to interpret the Apollo lunar data.

The full wave solutions, with the singly and multiply (two bounce) contributions accounted for in the analyses of scattering from very rough surfaces, provide an analytical/physical interpretation of the observed enhanced backscatter at both normal and oblique incidence. The single scatter programs have been transferred to the College of Engineering VAX. The programs are in Fortran IV. A concerted effort has also been made to enhance our ability to graphically represent our data. At present the computations of the multiply scattered field are executed on the Supercomputer facility at Cornell University. This computational work is supported through an NSF supercomputer grant.

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I. INTRODUCTION - STATEMENT OF THE PROBLEM

Physical optics and perturbation theories have traditionally been used to derive the like and cross polarized scattering cross sections for composite random rough surfaces. To this end two-scale models have been adopted and the rough surfaces are regarded as small scale surface perturbations that are superimposed on large scale, filtered surfaces. Thus, the scattering cross sections are expressed as sums of two cross sections. The first accounts for specular point scattering. It is given by the physical optics cross section for the filtered surface consisting of the large scale spectral components. The second accounts for Bragg scattering. It is given by the cross section for the surface consisting of the small scale spectral components that ride on the filtered surface.

On applying the perturbed-physical optics approaches it is necessary to specify the wavenumber k_d where spectral splitting is assumed to occur between the large and small scale spectral components of the rough surface. Thus, a combination of perturbation theory and physical optics was applied to obtain the scattering cross sections for perfectly conducting random rough surfaces. The spectral splitting wavenumber was specified on the basis of the characteristics of the small scale surface and/or on the characteristics of the large scale surface. In general the restrictions on both the large and small scale surfaces cannot be satisfied simultaneously and using the perturbed-physical optics approaches the evaluation of the

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scattering cross sections critically depend on the specification of the spectral splitting wavenumber.

More recently the full wave approach has been used to determine the scattering cross sections for composite random rough surfaces of finite conductivity. Since the full wave solutions account for Bragg scattering and specular point scattering in a self-consistent manner, it is not necessary to decompose the surface into two surfaces with small and large roughness scales. However, when such a decomposition is implemented, the full wave solutions for the scattering cross sections is expressed in terms of a weighted sum of two cross sections. Thus, on adopting a two-scale model, the full wave solution resolves the discrepancies between solutions mostly based on physical considerations. In an attempt to draw more definite conclusions regarding the choice of k_d, it was varied over a wide range of values. It was shown that while, as exprected, the cross sections associated with the individual large and small scale surfaces critically depend upon the choice of k_d, the weighted sum of the like polarized cross sections remain practically insensitive to variations in k_d for $2.0 > \beta > 1.0$. Thus, provided that the large scale surface satisfies the radii of curvature criteria (associated with the Kirchhoff approximations) the full wave solutions for the like polarized scattering cross sections based on the two-scale model are practically indiependent of the specified value of k_d.

On applying the full wave approach to evaluate the like and cross polarized scattering cross sections for two-scale models of composite rough surfaces, several assumptions are made to facilitate the computations.

The first assumption is that the large and small scale surfaces are statistically independent. It would seem reasonable to make such an assumption if the two surfaces are results of independent processes. For the general case, however, one cannot assume statistical independence of the large and small scale surfaces.

The second simplifying assumption that is made is that the mean square slope for the total surface was approximately equal to the mean square slope for the filtered large scale surface.

The third assumption is that the mean square height of the total rough surface is large compared to a wavelength, and the surface height characteristic function for the total surface is negligibly small compared to unity.

Finally, the physical optics approximation for the cross polarized backscatter cross section is zero. As a result, the cross polarized backscatter cross section for the filtered surface is set equal to zero when the two-scale model is used. However, for backscatter, only the specular points on the rough surface do not depolarize the incident wave.

A unified formulation has also been derived for the like and cross polarized cross sections for all angles of incidence. These solutions are compared with earlier solutions based on a two-scale model of the random rough surface. Thus, the simplifying assumptions, that are common to all the earlier solutions based on two-scale models of the rough surface, are carefully examined. It is shown that while the full wave solutions for the like polarized scattering cross sections based on the two-scale model are in reasonable agreement (within 3 db) with the unified full wave solutions, the two solutions for the cross polarized cross sections differ very significantly (about 15 db).

Using the unified full wave approach it is therefore possible to analyze more realistic models of propagation paths over the sea surface without resorting to the artificial decomposition of the irregular terrain into large and small scale surfaces.

Recent work with synthetic aperture radars has shown that the modulation of the scattering cross sections by ocean currents cannot be adequately accounted for as specular point or Bragg scattering. Thus, analyses based on the physical optics approach or on perturbation theory are in general, not valid, nor are any of the two-scale models appropriate. For example, in the case of backscatter at normal incidence, solutions based on the two-scale models cannot adequately distinguish between the vertical and horizontal like polarized cross sections. However, the full wave approach which accounts for specular point scattering and Bragg scattering in a unified self-consistent manner can properly distinguish between the two like polarized cross sections at normal incidence. This backscatter measurement at normal incidence, can provide sufficient information on wind speed and direction. Similarly, the full wave analysis has the potential to be successfully applied to problems of ship wake detection.

Several important modifications to the unified full wave solutions need to be made. The solutions are based on a second order iteration of the rigorous telegraphists' equations for the wave amplitudes. Higher order iterations need to be considered in order to account for multiple scattering by the rough surface. In addition, contributions to the scattered fields from the shadowed portions of the rough surface were ignored. The contributions from these shadow regions need to be examined. They are of particular significance for scattering near grazing incident angles θ when the Rayleigh roughness parameter $\beta = 4 k_0^2 <h^2> \cos^2$ is small (k_0 is the free space wavenumber and $<h^2>$ is the mean square height).

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In order to derive the mean values for the like and cross polarized scattering cross sections, it is necessary to ascertain the two point joint probability density functions for the rough surface height h and slopes $\bar{n}$. To facilitate the evaluation of the statistical average, it is usually assumed that the rough surface height and slopes are statistically independent and $p(\bar{n},\bar{n}') = p(\bar{n})\delta(\bar{n}-\bar{n}')$ (δ is the Dirac delta function). The impact of these assumptions need to be examined. Furthermore, it is usually assumed that the surface height and slope statistics are Gaussian. It is necessary to examine the effects of non Gaussian surface statistics. Anisotropic models of the rough surfaces (such as surfaces with swells and ship wakes) need to be considered. The rough surface autocorrelation function is not necessarily assumed to be Gaussian in this work. Rather, it is derived from realistic models of rough surfaces. The effects of different surface height autocorrelation functions or their Fourier transforms the surface height spectral density functions need to be examined.

The full wave approach can be used to evaluate the bistatic scattering cross sections for all incident and scattered wave directions. In this work, backscatter is emphasized. Recent work on scattering from rough surfaces and particles with irregular shapes indicates that the full wave approach correctly predicts backscatter enhancement from surfaces with different roughness scales.

In this work, the rough surfaces are characterized by a complex permittivity to account for its finite conductivity. This has an important impact upon both single scattering and multiple scattering by rough surfaces.

A documented computer code for the evaluation of the like and cross polarized cross sections will be developed. These codes will be no more difficult to implement than those based on the hybrid, perturbed-physical optics approach.

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Finally, a concerted effort will be made to obtain experimental validation of the analytical/numerical results.

2. SUMMARY OF RESULTS

During the period of this contract (July 1, 1987 - June 30, 1990) the principal investigator presented twenty-four (24) papers at scientific/ technical meetings (see Item (7.1a)) and five (5) additional papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item (7.1b)). Twenty-six (26) papers were submitted to Journal Editors for review (see Item (7.2)), and eighteen (18) were accepted for publication (see Item (7.3)). Twenty-two (22) papers were published in journals and conference proceedings (see Item (7.4)) and reprints of these papers have been submitted along with the six (6) semiannual progress reports. One (1) Interim Report and three (3) M.S. Theses have been completed during this reporting period (see Item (7.5)), copies were submitted with the Progress Reports). Two (2) Ph.D. Theses based on the research conducted under this contract will be completed by the end of next year (see Section 4). Details of the research results are provided in the reprints submitted with the Semi Annual Progress Reports and the preprints of manuscripts sent directly to the project monitor.

The principal results are summarized here.

1. Two separate approaches have been developed to account for multiple scatter from rough surfaces. The first approach involves a second order iterative solution. In the high frequency limit it is shown that these results correspond to one bounce (single scatter) and two bounces (multiple scatter) of the incident wave from the surface. The second approach involves the numerical solution of the generalized telegraphists' equations for the scattered wave amplitudes. To this end the radiation wave spectrum is discretized and the resulting set of first order coupled differential equations are solved numerically. This work is currently in

progress and only preliminary results have been obtained. This numerical solution contains the total field (the single and the multiple bounce contributions). Only one dimensionally rough surfaces are considered when this numerical approach is used.

2. In the high frequency limit shadowing is accounted for by limiting the local angles of incidence and scatter to less than 90°. Thus if $\bar{n}$ and $\bar{n}'$ are unit vectors normal to the surface and in the direction of propagation respectively, then this condition is satisfied if $-\bar{n}^i \cdot \bar{n} > 0$. This is referred to as self-shadow. In addition, it is assumed in the high frequency limit, that the fields vanish below the local tangent planes at the points where $\bar{n}^i \cdot \bar{n} = 0$. This shadowing is due to obstruction by distant topographical features. In the low frequency limit it is only necessary to account for self shadow since the fields below this local tangent plane cannot be ignored (see Item (7.2),xxv).

3. The random rough surfaces are usually characterized by Gaussian surface height and slope probability density functions. In this work, a broad family of non Gaussian probability density functions are considered. These are based on the Gamma functions of order K. For K = 1, the marginals of the joint probability density funciton of the surface height is exponential while for $K \to \infty$ (for all practical purposes $K \geq 25$) the marginals reduce to the Gaussian probability density function. Methods based on the examination of the tilt modulation of the scattering cross sections are suggested to remotely determine the appropriate probability density function (order K) that most closely represents the statistical characterization of the surface under observation.

4. To determine the rough surface cross sections, the random rough surfaces need to be characterized by their joint characteristic functions for the surface heights at two separate points. To this end it is also necessary to know the surface height spectral density function. Both

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Gaussian and non Gaussian spectral density functions have been considered in this work.

5. The medium below the rough interface is characterized by its complex permittivity and permeability. Thus conduction currents and displacement currents are accounted for in the analysis. In limiting cases, both perfect conductors and perfect dielectrics can be considered for the reflection as well as the transmission scattering problems.

6. To make the problem of evaluating the scattering cross sections of random rough surfaces more tractable, it is usually assumed that the rough surface height and slopes are statistically uncorrelated. In an attempt to examine the validity of this assumption random rough surfaces that vary in height, only in one dimension, are examined in detail. In order to simplify the analytical expressions for the scattered fields, the surface is also assumed to be perfectly conducting. Thus these random rough surfaces are characterized by four dimensional Gaussian joint probability density functions for the surface heights and slopes at two distinct points. The surfaces are also assumed to be slightly rough in order to determine the conditions for the coalescence of the full wave solutions with the small perturbation and specular point solutions. A preprint of this paper has been sent to the project monitor.

7. The observed phenomena of enhanced backscatter from very rough surfaces (including particles with rough surfaces) has been examined in some detail. The effects of varying the angles of incidence, the material below the interface, the surface mean square slope and height and the rough surface correlation lengths are considered. It is shown that at oblique angles ($\theta_o > 20^o$) single scatter is the principal contributor to the observed enhanced backscatter, while for near normal incidence the single scattered and multiply scattered contributions to the field add constructively or

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destructively about the backscatter direction.

8. During this reporting period several investigations were conducted to determine the scattering cross sections of rough surfaces that are modified by the presence of oil slicks naturally occurring or due to deliberate or accidental oil spills) ship wakes, swells and other anisotropic surface features. The motivation for this work is remote detection of these special features of the rough surface.

9. For the vector problem of electromagnetic scattering by two dimensional rough surfaces, the excitations considered are in general elliptically polarized waves, including the special cases; vertically, horizontally, right and left circular polarized waves. Thus, these results can be applied directly to polarimetric remote sensing.

10. As in the past, several attempts have been made to obtain experimental validation of the numerical/analytical results based on the full wave approach.

The University of Nebraska is currently in the process of setting up an optical scatterometer and Scanning Tunnelling Microscope facility (with a 75 micrometer dual scan for the STM and the Atomic Force Microscope for conducting and non conducting surfaces). Therefore, current attempts at experimental validation are restricted to comparison with data obtained from external sources. To this end, the full wave unified and two scale solutions have been used to interpret the Apollo lunar data. This data represents quasi specular reflection (from Apollo 14 through 16) off the moon surface to the earth at angles of incidence from about 10° to 85°. The full wave solution properly accounts for the significant rise in the normalized scattering cross section at around 80° just before rough surface shadowing needs to be accounted for in the analysis.

The full wave solutions, with the singly and multiply (two bounce)
contributions accounted for in the analysis of scattering from very rough sur-
faces, provide an analytical/physical interpretation of the observed enhanced
backscatter at both normal and oblique incidence (see Item #7, Section 2).

The single scatter programs that were executed previously on the CDC
computers at the University have been transferred to the College of Engineering
VAX. The programs are in Fortran IV and batch jobs are usually executed
within 24 hours. Smaller jobs can be executed practically in real time.
A concerted effort has also been made to enhance our ability to graphically
represent our data. Thus, for instance, the enhanced backscatter phenomena
can be viewed in three dimensions as surfaces whose distances from the
origin are proportional to the bistatic cross sections ($\sigma^{PP} + \sigma^{QP}$
P,Q = V (vertical), H (horizontal) polarizations). Illustrations of
these data are shown in Figures (9.1) and (9.2).

At present the computations of the multiply (two bounce) scattered
field are executed on the Supercomputer facility at Cornell University.
This computational work is supported through an NSF supercomputer grant.
Magda El-Shenawee (Ph.D. student) has taken two short courses at Cornell
University on the efficient use of Supercomputers.

3. DESCRIPTION OF RESEARCH

Detailed description of the analytical and numerical techniques used in these investigations and their applications to engineering and technology are given in the reprints and preprints of the scientific manuscripts submitted with the six (6) Semi Annual Progress Reports (See List of Publications, Section 7 and Appendix).

4. PERSONNEL SUPPORTED BY THIS CONTRACT

In addition to the principal investigator, Ezekiel Bahar, the main contributors to this research project are Mary Ann Fitzwater (Research Associate through 1988), and five (5) Graduate Research Assistants).

During this reporting period the following students received their M.S. degrees in Electrical Engineering. Copies of their theses were submitted with the Semi Annual Progress Reports (see Item #(7.5)).

(i) Robert D. Kubik

(ii) Yan-Feng Li

(iii) Guorong Huang

The Ph.D. dissertation of Magda El-Shenawee and Xiaochuan Shi should be completed by the end of next year.

5. ACKNOWLEDGMENTS

6. CONCLUDING REMARKS

The research group at the University of Nebraska-Lincoln has over the three year duration of the ARO contract, satisfied all the research objectives in the original proposal. Several new objectives need to be considered for future work in this field. They include the evaluation of the scattering cross sections of foliage covered terrain. To exploit recent advances in polarimetric radar techniques, it is also necessary to evaluate all the sixteen (16) Mueller matrix elements (not only the scattering cross sections). For slightly rough surfaces it is necessary to evaluate both the coherent and incoherent scattering cross sections. This would significantly contribute to resolving some of the questions raised recently on the validity of the small perturbation and Kirchhoff approaches to rough surface scattering. In addition, excitation by real sources rather than uniform plane wave should be considered.

Suggested topics for future consideration by the researchers at the University of Nebraska are listed below.

1. Use rigorous mathematical/physical models of pertinent engineering/ scientific problems and employ a judicious combination of theoretical, applied and computational mathematics to solve them. These solutions should be applicable to a very broad class of rough surfaces and to ultra wideband radars. No artificial scaling parameters or "effective" median parameters should be used in this work.

2. Determine the full wave like and cross polarized incoherent diffuse scattered intensities for finitely conducting leaves characterized by their rough surface height autocorrelation functions (or surface height spectral density functions).

3. Determine the full wave like and cross polarized incoherent diffuse scattered intensities for finitely conducting stems modeled as cylinders with random rough surfaces.

4. Determine the full wave like and cross polarized incoherent diffuse scattered intensities for finitely conducting random rough terrain characterized by realistic surface height autocorrelation functions.

5. Determine the full wave like and cross polarized incoherent diffuse scattered intensities for propagation paths involving vegetation (leaves and stems) as well as rough terrain.

6. Develop techniques to discriminate between clutter due to vegetation and vegetation covered terrain and radar signatures from specific targets. In particular special consideration should be given to the existence of transmission windows in either the frequency domain or the spacial (angular) domain.

7. Full wave solutions for the (4 x 4) Mueller matrix elements should be used to evaluate polarimetric radar techniques for target/clutter discrimination.

8. Analytical and numerical determination of the like and cross polarized multiple scatter contributions to the total scattered field from one and two dimensionally rough surfaces.

9. Consider the effects of rough surface height and slope correlations on the evaluation of the like and cross polarized scattering cross sections of one and two dimensionally rough surfaces. Thus the random rough surface is characterized in general by a six dimensional joint probability density function for heights and slopes at two points.

10. Consider the impact of self shadow (due to restrictions on local angles of incidence and scatter) and the impact of shadowing due to neighboring surface obtrusions, on the scattered field.

11. Determine the transmission scattering cross sections for rough surfaces. Thus the like and cross polarized intensities diffusely scattered across irregular boundaries need to be evaluated.

12. For slightly rough surfaces, both the coherent and incoherent scattering cross sections should be evaluated.

13. Excitation by real sources rather than uniform plane waves should be considered.

14. A major effort can now be made to compare the analytical/numerical results with both in situ measurements (over the earth's surface) as well as controlled laboratory experiments. To this end the Electrical Egnineering Department is setting up an optical scattero-meter, microwave anechoic chamber and tunnelling microscope facility in conjunction with the Center for Electro-Optics in the College of Engineering and Technology.

The Principal Investigator has had wide experience in constructing laboratory models (earth-ionosphere waveguide) to experimentally examine the validity of analytical/numerical solutions. He has compared the predictions based on the full wave analysis with in situ experimental data over the earth's surface as well as with controlled laboratory experiments. He has interest and experience to conduct research in analytical, numerical and experimental areas listed above.

7. LIST OF PUBLICATIONS BY THE PRINCIPAL INVESTIGATOR
DURING PERIOD OF ARMY CONTRACT

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.Ia) Papers Presented at Technical Meetings

(i) XXIInd General Assembly of the International Union of Radio Science, Tel Aviv, Israel, August 24-September 21, 1987, Paper Presented "Radar Cross Sections of Rough Terrain and Vegetation Covered Terrain," Member of U.S. National Research Council Delegation.

(ii) International Union of Radio Science (URSI) Meeting at the University of Colorado, Boulder, January 5-8, 1988, "Backscatter Enhancement from Sparsely Distributed Large Particles with Rough Surfaces," with M. A. Fitzwater.

(iii) 1988 SPIE Technical Symposium on Optics, Electro-Optics and Sensors - Wave Propagation and Scattering in Varied Media, Orlando, Florida, April 4-8, 1988, "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater.

(iv) 1988 IEEE AP-S International Symposium and URSI Radio Science Meeting, Syracuse University, Syracuse, New York, June 6-11, 1988, "Conditions for Coalescence of the Full Wave Solution for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions in the Low and High Frequency Limits - Theory and Experiment."

(v) 1988 International Geoscience and Remote Sensing Symposium, Edinburgh University, Edinburgh, United Kingdom, September 13-16, 1988. "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," (FRA-211).

(vi) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, U.S.S.R., September 19-23, 1988. "Stokes Parameters for Propagation Media with Random Distributions of Irregular Shaped Particles."

(vii) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, U.S.S.R., September 19-23, 1988. "Scattering and Depolarization and Enhanced Backscatter from Random Rough Surfaces."

(viii) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, Colorado, January 4-6, 1989, "Full-Wave Copolarized Neospecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. Fitzwater.

(ix) IEEE AP-S International Symposium and URSI Radio Science Meeting, June 26-30, 1989, San Jose, California, "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media."

(x) 1989 CRDEC Scientific Conference on Osbscuration and Aerosol Research, Aberdeen, MD, June 26-30, 1989, "Transmission Scattering and Depolarization Across Rough Surfaces - Full Wave Solutions," with Guorong Haung.

(xi) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces Unified Full Wave Approach," with R. Kubik.

(xii) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Interpretation of the Apollo Lunar Surface Data Using the Unified Full Wave and the Two Scale Full Wave Approach," with M. Haugland.

(xiii) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989, "Diffuse Specific Intensities and Backscatter Enhancement for Random Distribution of Finitely Conducting Particles with Rough Surfaces."

(xiv) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989, "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths."

(xv) National Science Foundation Workshop on Future Directions in Electromagnetic Research, Panel Member on Scattering and Inverse Scattering Techniques, July 27, 1989, Boston, Massachusetts, Invited Paper on Electromagnetic Scattering by Randomly Rough Boundaries.

(xvi) URSI International Symposium on Electromagnetic Theory at the Royal Institute of Technology, Stockholm, Sweden, August 14-17, 1989, "Physical Models of Non-specular Scattering in Irregular Stratified Media."

(xvii) International Union of Radio Science Commission F Symposium on Radio and Non-ionized Media at La Londe-les-Maures, France, September 11-15, 1989, "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik.

(xviii) Scientific Conference on Chemical Defense Research, U.S. Army Research Chemical Research Development and Engineering Center, Aberdeen, Maryland, November 14-17, 1989, Statistics for Identifying a Contaminated Rough Surface by Polarized IR Scattering: Full Wave Approach with S. M. Haugland and A. H. Carrieri.

(xix) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, CO, January 3-5, 1990, Electromagnetic Scattering and Depolarization Across Rough Surfaces--Full Wave Solution with G. Huang.

(xx) First Los Alamos Symposium on Ultra-Wideband Radar, Los Alamos National Laboratory, March 5-8, 1990, "Rough Surface Scattering Cross Sections for Ultra-Wideband Radars."

(xxi) IEEE AP-S International Symposium and URSI Radio Science Meeting, May 7-11, 1990, Dallas, Texas, "Full Wave Multiple Scattering from Rough Surfaces with M. El-Shenawee.

(xxii) International Union of Radio Science (URSI, Commission F) Conference on Signature Problems in Microwave Remote Sensing of the Surface of the Earth, Hyannis, MA, May 16-18, 1990, "Remote Sensing of the Sea Surface Contaminated by Monomolecular Oil Slick: Full Wave Approach," with R. Kubik.

(xxiii) 1990 International Geoscience and Remote Sensing Symposium (IGARSS '90) Symposium on Remote Sensing Science for the Nineties, University of Maryland, College Park, MD, May 20-24, 1990, "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscatter Radar Cross Sections: Full Wave Approach, with Y. F. Li.

(xxiv) 1990 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 25-28, 1990, "Multiple Scattering of Electromagnetic Waves from Coated Rough Surfaces," with Mark Haugland.

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(7.1b) Papers Accepted for Presentation at Technical Meetings

   (i) XXIIIrd General Assembly of the International Union of Radio Science, Prague, Czechoslovakia, Aug. 28 - Sep. 5, 1990, "Radiowave Propagation Over Terrain Characterized by a Broad Range of Roughness Scales and Varying Electromagnetic Parameters," Invited Paper.

  (ii) International Union of Radio Science Symposium on Scattering from Random Media (Joint Session B/F), Prague, Czechoslovakia, Aug. 28 - Sep. 5, 1990, "Like and Cross Polarized Backscatter Enhancement and Antispecular Transmission from Finitely Conducting Two Dimensionally Rough Surfaces."

 (iii) Advisory Group for Aerospace Research and Development Fall 1990, Electromagnetic Wave Propagation Panel Symposium on Use or Reduction of Propagation and Noise Effects in Distributed Military Systems, Rethymno, Crete, Greece, Oct. 15-19, 1990, "Utilization or Reduction of the Effects of Sea Clutter for Real and Synthetic Aperture Polarimetric Radars."

  (iv) The Fourth Biennial IEEE Conference on Electromagnetic Field Computation, Toronto, Canada, Oct. 22-24, 1990, "Use of Supercomputers to Evaluate Singly and Multiply Scattered Electromagnetic Fields from Rough Surfaces," with M. El-Shenawee.

   (v) 1990 U.S. Army Chemical Research Development and Engineering Center Scientific Conference on Chemical Defense Research, Aberdeen, MD, Nov. 13-16, 1990, "Computation of Mueller Matrix Elements for Irregular Stratified Media - Full Wave Approach," with Mark Haugland.

(7.2) Papers Submitted to Journal Editors for Review

   (i) "Full Wave - Co-Polarized Nonspecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater.

  (ii) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M. A. Fitzwater.

 (iii) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater.

  (iv) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater.

  (v) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater.

  (vi) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater.

 (vii) "Non-Specular Scattering by Irregular Layered Media - Full Wave Approach.

(viii) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik.

  (ix) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland.

  (x) "Physical Models of Nonspecular Scattering in Irregular Stratified Media."

  (xi) "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik.

 (xii) "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited Paper on Review of Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel.

(xiii) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths.

 (xiv) "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces."

  (xv) "Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions,

 (xvi) "Unified and Two Scale Full Wave Solutions to Interpret Apollo Lunar Surface Data," with M. Haugland.

(xvii) "Tilt Modulation of Synthetic Aperture Radar Backscatter Cross Sections: Unified Full Wave Approach," with R. Kubik.

(xviii) "Computer Simulation of Synthetic Aperture Polarimetric Images - Unified Full Wave Approach," with R. Kubik.

 (xix) "Electromagnetic Scattering and Depolarization Across Rough Surfaces - Full Wave Solutions," with G. Huang.

  (xx) "Scattering Cross Sections for Composite Models of Non-Gaussian Rough Surfaces: Unified Full Wave Approach.

 (xxi) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Models of Non-Gaussian Rough Surfaces: Unified Full Wave Approach."

(xxii) "Statistics for Identifying Contaminated Rough Surfaces by Polarized IR Scattering: Full Wave Approach," with S. M. Haugland and A. H. Carrieri.

(xxiii) "Full Wave Multiple Scattering from Rough Surfaces," with M. El-Shenawee.

(xxiv) "Acoustic Scattering by Two-Dimensionally Rough Interfaces Between Dissipative Acoustic Media - Full Wave, Physical Acoustics and Perturbation Solutions."

(xxv) "Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions." Revised.

(xxvi) "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscattered Radar Cross Sections: Full Wave Approach," with Yan-Feng Li.

(7.3) Papers Accepted for Publication

(i) "Enhancement of the Backscattered Diffuse Specific Intensities from Random Distributions of Finitely Conducting Particles with Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America.

(ii) "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America, A.

(iii) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Optics, Electro-Optics, and Sensors.

(iv) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater, Journal of Wave-Material Interaction.

(v) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater, Journal of Wave-Material Interaction.

(vi) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," Journal of Geophysical Research - Ocean.

(vii) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M. A. Fitzwater, IEEE Transactions on Antennas and Propagation.

(viii) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, Journal of the Optical Society of America, A.

(ix) "Non Specular Scattering by Irregular Layered Media," Proceedings of the 1988 Scientific Conference on Obscuration and Aerosol Research.

(x) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik, Proceedings of the IGARSS '89 Conference on Remote Sensing.

(xi) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS '89 Conference on Remote Sensing.

(xii) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium.

(xiii) "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces, Proceedings of Progress in Electromagnetic Research Symposium.

(xiv) "Physical Models of Nonspecular Scattering in Irregular Stratified Media," Proceedings of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory.

(xv) "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik, Proceedings of the International Union of Radio Science Symposium on Radio Wave Propagation and Remote Sensing.

(xvi)   "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited Paper
         - Review on Progress and Emerging Future Directions - Scattering and Inverse
         Scattering Techniques Panel, Proceedings of the National Science Foundation
         Workshop on Future Direction in Electromagnetic Research.

(xvii)   "Full Wave Solutions for the Scattering of Acoustic Waves Excited by
         Arbitrary Source Distributions in Irregular Layered Media," Wave Motion.

(xviii) "Full Wave Multiple Scattering from Rough Surfaces," with M. El-Shenawee,
         Proceedings of the IEEE AP-S International Symposium and URSI Radio Science
         Meeting.

(7.4) Papers Published in the Technical Literature and Submitted with the six (6) Semi-Annual Reports

(i) "Full Wave Theory and Controlled Optical Experiments for Enhanced Scattering and Depolarization by Random Rough Surfaces," with M. A. Fitzwater, Optics Communications, Vol. 63, No. 6, pp. 355-360, September 1987.

(ii) "Enhancement of the Backscattered Diffuse Specific Intensities from Random Distributions of Finitely Conducting Particles with Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America, A, Vol. 5, pp. 89-98, Jan. 1988.

(iii) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," Journal of Wave-Material Interaction, Vol. 3, No. 3, 199-218, July (1988).

(iv) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Wave Propagation and Scattering in Varied Media, Vol. 927, 78-87, April 6-8 (1988).

(v) "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America A, Vol. 5, 1873-1883, November (1988).

(vi) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater, Journal of Wave-Material Interaction, Vol. 3, No. 2, 1973-187, April (1988).

(vii) "Backscatter Enhancement of Infrared and Optical Radiation from Finitely Conducting Particles with Smooth and Very Rough Surfaces - First Order and Multiple Scatter," with M. A. Fitzwater, Proceedings of the 1987 Scientific Conference on Obscuration and Aerosol Research.

(viii) "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media," Radio Science, Vol. 28, No. 5, 749-759, September-October (1988).

(ix) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, Journal of the Optical Society of America, A, Vol. 6, pp. 33-43, January, 1989.

(x) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," with C, M. Herzinger and M. A. Fitzwater, Journal of Geophysical Research - Oceans, Vol. 94, No. C2, pp. 2159-2169, February, 1989.

(xi) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M. A. Fitzwater, IEEE Transactions on Antennas and Propagation, Vol. AP-S 37, No. 12, pp. 1609-1616, December, 1989.

(xii) "Non Specular Scattering by Irregular Layered Media," Proceedings 1988 Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, CRDEC-SP, pp. 1-8, 1989.

(xiii) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada, IEEE #89CH2768-0, Vol. 3, pp. 1296-1299, July 4-10, 1989.

(7.5) Interim Reports and M.S. Thesis Completed During This Reporting Period

  (i) "Synthetic Aperture Radar Images for Swell Using the Unified Full Wave Method," with R. D. Kubik.

 (ii) "Scattering Cross Section Modulation of a Synthetic Aperture Radar Resolution Cell with Application to SAW Imaging Unified Full Wave Approach," by Robert D. Kubik.

(iii) "Scattering and Depolarization of Electromagnetic Waves from Random Rough Surfaces with Non-Gaussian Statistics - Full Wave Solution by Yan-Feng Li.

 (iv) "Transmission Scattering and Depolarization of Electromagnetic Waves Across Rough Interfaces, Full Wave Approach," by Guorong Huang.

8. APPENDIX

SEMI-ANNUAL PROGRESS REPORTS NUMBERS 1-6

PROGRESS REPORT #1

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 July 1987 - 31 December 1987

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough
                         Terrain and Sea-A Unified Full Wave
                         Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP
    DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

        See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED
    DURING THIS REPORTING PERIOD:

        Professor Ezekiel Bahar - Principal Investigator

Ezekiel Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NE 68508

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1) Papers Presented at Technical Meetings

(i) XXIInd General Assembly of the International Union of Radio Science, Tel Aviv, Israel, August 24-September 21, 1987, Paper Presented "Radar Cross Sections of Rough Terrain and Vegetation Covered Terrain," Member of U.S. National Research Council Delegation.

(7.2) Papers Submitted to Journal Editors for Review

(i) "Full Wave - Co-Polarized Nonspecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, submitted for review.

(ii) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M. A. Fitzwater, submitted for review.

(iii) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, submitted for review.

(7.3) Papers Accepted for Publication

(i) "Enhancement of the Backscattered Diffuse Specific Intensities from Random Distributions of Finitely Conducting Particles with Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America, in press.

(7.4) Papers Published in the Technical Literature and Submitted with this Report

(i) "Full Wave Theory and Controlled Optical Experiments for Enhanced Scattering and Depolarization by Random Rough Surfaces," with M. A. Fitzwater, Optics Communications, Vol. 63, No. 6, pp. 355-360, September 1987.

OUTLINE OF RESEARCH FINDINGS

During the reporting period (July 1-December 31, 1987), the principal investigator presented an invited paper at the XXIInd General Assembly of the International Union of Radio Science (see Item (7.1)(i)). He also attended the URSI General Assembly as an official U.S. Delegate appointed by the U. S. National Research Council. Three technical/scientific manuscripts were prepared and submitted for publication (see Items (7.2)(i)-(iii), preprint of Item (7.2)(iii) also submitted to contract monitor). One paper was accepted for publication by the Journal of the Optical of America (see Item (7.3)(i) and one paper was published in Optics Communications (see Item (7.4)(i)).

On December 9-10, 1987, the contract monitor Dr. W. A. (Bud) Flood visited the University of Nebraska-Lincoln (UNL) and discussed with the principal investigator and his research associates the progress made in the investigations of the UNL group during this reporting period. During his visit, Dr. Flood also received a series of plots he requested of the like and cross polarized scattering cross sections for rough surfaces with complex permitivities and surface height statistics specified by him. As per his request during the meeting, a set of computer print-outs and plots were also mailed to Dr. Flood on December 23, 1987. Data was provided for both the bistatic scattering cross sections as functions of scatter angle in the plane of incidence as well as the backscatter cross sections as functions of the angle of incidence.

The observed like and cross polarized backscatter enhancement was predicted as a first order effect on the basis of an iterative-closed form solution to the full wave-telegraphists' equations. This approximation

of the full wave solution therefore does not account for multiple scattering by the rough surface. At present the principal investigators has also derived analytical expressions for the second order-multiply scattered field and this work, in its two dimensional version (one dimensional rough surface) has been given to a graduate student for the purpose of preparing a computer code to calculate the second order multiply scattered fields. The information derived from this phase of the research project is to be used to generate criteria regarding the cases for which multiple scatter significantly modifies the first order results and to determine the major impact of multiple scatter on the total scattered field--whether it is a very diffuse contribution or whether (as some conjecture), it contributes to the observed enhanced backscatter.

The full wave solutions for the horizontally polarized bistatic scattering cross sections of one dimensional perfectly conducting surfaces were also compared with the computed data obtained with a Monte Carlo technique by E. I. Thorsos and A. Ishimaru (at the University of Washington at Seattle, Washington). Since the mean square slopes of the surfaces examined were very small compared to unity and since the correlation between the surface heights and slopes is proportioned to the mean square slopes, this correlation was ignored in these full wave computations. It is shown that for all the cases provided to Dr. Flood by Thorsos and Ishimaru, these full wave solutions were in very good agreement with their results. At present the full wave computer code is being modified to account for all the correlations between the slopes and heights at two points on the rough surface. This phase of the research project which may have to be executed

on a supercomputer, should shed light on the different conclusions reached by the researchers at UNL and UW at Seattle. It should be noted that for the purposes of the full wave analysis, the excitation is assumed to be an obliquely incident uniform plane wave, however the results provided by the UW researchers are for an obliquely incident "wave" with a Gaussian "taper"--not transverse to the direction of the incident wave but transverse to the mean reference plane of the rough surface--such a "tapered wave" does not satisfy Maxwell's equations.

PROGRESS REPORT #2

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 January 1988 - 30 June 1988

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough
                         Terrain and Sea-A Unified Full Wave
                         Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP
    DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

        See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED
    DURING THIS REPORTING PERIOD:
        Professor Exekiel Bahar - Principal Investigator
        Dr. M. A. Fitzwater - Research Associate
        Graduate Research Assistants

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Department of Electrical Engineering
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Lincoln, NB 68508

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings

   (i) International Union of Radio Science (URSI) Meeting at the University of Colorado, Boulder, January 5-8, 1988. "Backscatter Enhancement from Sparsely Distributed Large Particles with Rough Surfaces," with M. A. Fitzwater.

   (ii) 1988 SPIE Technical Symposium on Optics, Electro-Optics and Sensors - Wave Propagation and Scattering in Varied Media, Orlando, Florida, April 4-8, 1988. "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater.

   (iii) 1988 IEEE AP-S International Symposium and URSI Radio Science Meeting, Syracuse University, Syracuse, New York, June 6-11, 1988. "Conditions for Coalescence of the Full Wave Solution for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions in the Low and High Frequency Limits - Theory and Experiment."

(7.1b) Papers Accepted for Presentation at Technical Meetings

   (i) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, USSR, September 19-23, 1988. "Stokes Parameters for Propagation Media with Random Distributions of Irregular Shaped Particles."

   (ii) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, USSR, September 19-23, 1988. "Scattering, Depolarization and Enhanced Backscatter from Random Rough Surfaces."

(7.2) Papers Submitted to Journal Editors for Review

   (i) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Optics, Electro-Optics, and Sensors

   (ii) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity" with M. A. Fitzwater, Journal of Wave-Material Interaction

   (iii) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater, Journal of Wave-Material Interaction.

(7.3) Papers Accepted for Publication

   (i) "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America, A, in press.

   (ii) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M.A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Optics, Electro-Optics, and Sensors, in press.

   (iii) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M.A. Fitzwater, Journal of Wave-Material Interaction, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

   (i) "Enhancement of the Backscattered Diffuse Specific Intensities from Random Distributions of Finitely Conducting Particles with Rough Surfaces," with M.A. Fitzwater, Journal of the Optical Society of America, A, Vol. 5, pp. 89-9c, Jan. 1988.

OUTLINE OF RESEARCH FINDINGS

During the reporting period (1 January–June 30, 1988), the principal investigator presented three papers at scientific/technical meetings (see Item (7.1a)) and he has been invited to present two papers at the International Working Group Meeting on Wave Propagation in Random Media (see Item (7.1b)). Three technical/scientific manuscripts were prepared and submitted for publication (see Item (7.2)). Three papers were accepted for publication (see Item (7.3)) and one paper was published in the Journal of the Optical Society of America A (see Item (7.4)) and reprints have been submitted with this Report.

The principal investigator visited with the contract monitor, Dr. W. A. (Bud) Flood, while attending the IEEE AP-S International Symposium and URSI Radio Science Meeting at the University of Syracuse, Syracuse, New York, June 6-11, 1988. An oral report was presented on the research conducted by the UNL group.

In order to evaluate the mean values of the scattering cross sections for random rough surfaces, it is necessary to characterize the surfaces by their height and slope joint characteristic function $X_2(h(\bar{r}),h(\bar{r}'),\bar{n}(\bar{r}),\bar{n}(\bar{r}'))$ at points $\bar{r}$ and $\bar{r}'$ on the rough surface (h is the height and $\bar{n}$ is the normal to the surface) or its Fourier transform the joint probability density function, $p(h(\bar{r}),h(\bar{r}'),\bar{n}(\bar{r}),\bar{n}(\bar{r}'))$. Thus, for isotropic, homogeneous two dimensionally rough surfaces it is necessary to evaluate five dimensional integrals. These integrals account for all the correlations between the random surface height and slopes at two neighboring points on the rough surface. If it is assumed that the surface does not vary in the direction normal to the scattering plane, the scattering problem can be reduced to two uncoupled problems r the vertically and horizontally polarized waves since the scattered waves are not

In view of the fact that for this phase of our work the computations are very time-consuming even for one-dimensionally rough surfaces, one of the graduate research assistants associated with our investigations is attending a two-week workshop sponsored by the National Science Foundation at the Super Computer facility at Cornell University this summer. We expect to have access to the Super Computer facility at the CRDEC, Aberdeen, Maryland. Access to Super Computers (NSF or DOD) would facilitate the extension of this phase of our investigations to two dimensional models of rough surfaces.

PROGRESS REPORT #3

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 July 1988 - 31 December 1988

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough Terrain and Sea-A Unified Full Wave Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: _____Ezekiel Bahar_____

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

        See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

        Professor Ezekiel Bahar - Principal Investigator
        Dr. M. A. Fitzwater - Research Associate
        Graduate Research Assistants

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University of Nebraska
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7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings

(i) 1988 International Geoscience and Remote Sensing Symposium, Edinburgh University, Edinburgh, United Kingdom, September 13-16, 1988. "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," (FRA-211).

(ii) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, U.S.S.R., September 19-23, 1988. "Stokes Parameters for Propagation Media with Random Distributions of Irregular Shaped Particles."

(iii) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, U.S.S.R., September 19-23, 1988. "Scattering Depolarization and Enhanced Backscatter from Random Rough Surfaces."

(7.1b) Papers Accepted for Presentation at Technical Meetings

(i) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, Colorado, January 4-6, 1989. "Full-Wave Copolarized Neospecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater.

(ii) IEEE AP-S International Symposium and URSI Radio Science Meeting, San Jose, California, June 26-30, 1989. "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media."

(iii) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989. "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces Unified Full Wave Approach," with R. Kubik.

(iv) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989. "Interpretation of the Apollo Lunar Surface Data Using the Unified Full Wave and the Two Scale Full Wave Approach." with M. Haugland.

(v) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989. "Diffuse Specific Intensities and Backscatter Enhancement for Random Distribution of Finitely Conducting Particles with Rough Surfaces."

(vi) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989. "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths.

(vii) URSI International Symposium on Electromagnetic Theory at the Royal Institute of Technology, Stockholm, Sweden, August 14-17, 1989. "Physical Models of Nonspecular Scattering in Irregular Stratified Media."

(7.2) Papers Submitted to Journal Editors for Review

(i) "Non Specular Scattering by Irregular Layered Media - Full Wave Approach," Proceeding of the 1988 Scientific Conference on Obscuration and Aerosol Research.

(7.3) Papers Accepted for Publication

(i) "Bistatic Incoherent Scattering Cross Sections for Two-dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater, Journal of Wave-Material Interaction, Vol. 3, No. 2, 173-187, April (1988).

(ii) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," Journal of Geophysical Research - Ocean (in press).

(7.3) continued

(iii) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M. A. Fitzwater, IEEE Transactions on Antennas and Propagation (in press).

(iv) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, Journal of the Optical Society of America A, Vol 6, 33-43, January (1989).

(7.4) Papers Published in the Technical Literature and Submitted with This Report

(i) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," Journal of Wave-Material Interaction, Vol. 3, No. 3, 199-218, July (1988).

(ii) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Wave Propagation and Scattering in Varied Media, Vol. 927, 78-87, April 6-8 (1988).

(iii) "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America A, Vol. 5, 1873-1883, November (1988).

(iv) "Bistatic Incoherent Scattering Cross Sections for Two-dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater, Journal of Wave-Material Interaction, Vol. 3, No. 2, 173-187, April (1988).

(v) "Backscatter Enhancement of Infrared and Optical Radiation from Finitely Conducting Particles with Smooth and Very Rough Surfaces - First Order and Multiple Scatter," with M. A. Fitzwater, Proceedings of the 1987 Scientific Conference on Obscuration and Aerosol Research.

(vi) "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media," Radio Science, Vol. 28, No. 5, 749-759, September-October (1988).

(7.5) Interim Reports

(i) "Synthetic Aperture Radar Images for Swell Using the Unified Full Wave Method," with R. D. Kubik.

Outline of Research Findings

During the reporting period (1 July 1988 - 31 December, 1988), the principal investigator presented three papers at Scientific/Technical meetings (see Item (7.1a)) and seven papers have been accepted for presentation in the next few months (see Item (7.1b)). One paper was submitted for publication (see Item 7.2) and four papers were accepted for publication (see Item 7.3). Six papers were published (see Item 7.4) and reprints of these papers have been submitted with this report. An interim report on synthetic aperture radar images was submitted to the project monitor (see Item 7.5).

The contractor monitor Dr. W. A. (Bud) Flood visited the research group at the University of Nebraska-Lincoln in November, 1988. He was presented an oral report by the principal investigator and the graduate students involved with this project.

The full wave analytical and computational work on the horizontally and vertically polarized incoherent bistatic cross sections for one-dimensionally rough perfectly conducting surfaces is near completion. In this work, the random rough surface is characterized by a four-dimensional Gaussian probability density function for the surface heights and slopes at two points on the surface. It is also assumed that the surface height spectral density functions (and their Fourier transforms the surface height autocorrelation functions) are also Gaussian. Thus, all the correlations between the surface heights and slopes at two points on the rough surface are accounted for in the analysis.

In this work the corresponding physical optics and small perturbation solutions are also evaluated. It is shown that when the rough surface slopes are assumed to be negligibly small (as in the analysis of Rice (1951)), the full wave analysis reduces to the small perturbation results. However, when it is assumed that the major contributions to the scattered field come from

the neighborhoods of the stationary phase points, the full wave solutions are in agreement with the physical optics solutions. In general there is good agreement between the full wave, small perturbation and physical optics solutions for scattering in the near specular directions when the mean square slopes are very small compared to unity and mean square heights are very small compared to the wavelength of the electromagnetic excitations. However, for backscatter, this is not the case.

Since the full wave scattering coefficients involve expressions for the sine and cosines of the local angles of incidence and scatter, shadowing is intrinsically accounted for in the analysis. It is shown that where shadowing is deliberately ignored, all the integrals for the specular cross sections (and the horizontally polarized backscatter cross section) can be evaluated analytically. This work has shown that shadowing effects are very significant.

Surfaces characterized by different spectral density functions, but with the same mean square heights and correlation lengths are shown to have significantly different bistatic cross sections.

Progress has also been made involving the evaluations of the like and cross polarized cross sections for two dimensionally random rough surfaces. The medium below the rough interface is characterized by complex relative permittivities $\epsilon_r = \epsilon' - i\epsilon''$ with a positive or a negative real part (ϵ') and a negative imaginary part ($\epsilon'' \geq 0$ accounts for dissipation). The like and cross polarized scattering cross sections for vertically and horizontally polarized excitations can be evaluated for any direction in the upper half space and not just in the plane of incidence. Methods for presenting these new three dimensional data are presently under study.

The computer codes for scattering by two dimensionally rough surfaces have been generalized to account for both (vertical and horizontal) linearly polarized excitations as well as (right and left) circularly polarized excitations. Thus in addition to the four like and cross polarized cross sections

σ^{VV}, σ^{HH}, σ^{HV}, σ^{VH} (V-vertical, H-horizontal) four new cross sections σ^{RR}, σ^{LL}, σ^{LR}, σ^{RL} (R-right circular, L-left circular) can now be evaluated. These new results will be used to shed additional light on the interpretation of the experimental data.

Two approaches (by different students) are currently being investigated in order to account for multiple scattering. At this time only one dimensionally rough surfaces are considered for this phase of our work. In one approach we seek numerical solutions to the (full wave) generalized telegraphists' equations. A major difficulty with this approach involves the singular nature of these integro differential equations. The second approach involves the evaluation of a third order iterative solution to the telegraphists' equations. It is shown that in the high frequency limit (using stationary phase integration techniques) these third order iterative solutions correspond to incident waves that are specularly scattered twice by the rough surface. (The first and second order iterative solutions are the primary and single scatter solutions respectively). The principal problem with the evaluation of the third order iterative solutions involves the very large amount of computer time needed even for super computers. The principal investigator has been informed that he has been awarded 95 hours of computational time on the NSF supported Super Computer Center at Cornell University. This supercomputer Grant will facilitate progress in this phase of our research.

Progress has been made on the efficient evaluation of the radar cross sections for rough surfaces with arbitrarily oriented mean planes (with respect to the plane of incidence). The modulations of the scattering cross sections characterized by two angles; the tilt of the mean plane measured "in" the plane of incidence and the tilt of the mean plane measured "perpendicular" to the plane of incidence. This will facilitate the rapid evaluation of the scattering cross sections for rough surfaces that are tilt modulated by very large scale

terrain features. (These very large scale terrain features are assumed to be much larger than the dimensions of the surface area illuminated by the radar).

Progress has also been made on the evaluation of the scattering cross sections for surfaces with non-Gaussian height and slopes statistics using the unified full wave approach instead of the earlier solutions based on the two scale approach. Consideration is being given to practical ways that can be used to determine the rough surface statistics using these analytical studies.

References

Rice S.O. (1951), Reflection of Electromagnetic Waves from Slightly Rough Surfaces, The Theory of Electromagnetic Waves, Interscience Publishers INC, New York, NY.

PROGRESS REPORT #4

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 January 1989 – 30 June 1989

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough
                        Terrain and Sea-A Unified Full Wave
                        Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP
    DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

        See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED
    DURING THIS REPORTING PERIOD:

        Professor Ezekiel Bahar - Principal Investigator
        Graduate Research Assistants

Ezekiel Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NB 68508

LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES.

(7.1a) Papers Presented at Technical Meetings

(i) International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, Colorado, January 4-6, 1989, "Full-Wave Copolarized Neospecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M.Fitzwater.

(ii) IEEE AP-S International Symposium and URSI Radio Science Meeting, June 26-30, 1989, San Jose, California, "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media."

(iii) 1989 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 26-30, 1989, "Transmission Scattering and Depolarization Across Rough Surfaces -Full Wave Solutions," with Guorong Haung.

(7.1b) Papers Accepted for Presentation at Technical Meetings

(i) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces Unified Full Wave Approach," with R. Kubik.

(ii) International Geoscience and Remote Sensing Symposium, Vancouver, Canada, July 10-14, 1989, "Interpretation of the Apollo Lunar Surface Data Using the Unified Full Wave and the Two Scale Full Wave Approach," with M. Haugland.

(iii) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989, "Diffuse Specific Intensities and Backscatter Enhancement for Random Distribution of Finitely Conducting Particles with Rough Surfaces."

(iv) Progress in Electromagnetic Research Symposium, MIT, Cambridge, Massachusetts, July 25-26, 1989, "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths."

(v) National Science Foundation Workshop on Future Directions in Electromagnetic Research, Panel member on Scattering and Inverse Scattering Techniques, July 27, 1989, Boston, Massachusetts, Invited paper on Electromagnetic Scattering by Randomly Rough Boundaries.

(vi) URSI International Symposium on Electromagnetic Theory at the Royal Institute of Technology, Stockholm, Sweden, August 14-17, 1989, "Physical Models of Nonspecular Scattering in Irregular Stratified Media."

(vii) U.S. Army Research Chemical Research Development and Engineering Center, Aberdeen, MD, Nov.14-17,1989, Statistics for Identifying a Contaminated Rough Surface by Polarized IR Scattering: Full Wave Approach with S.M. Haugland and A.H. Carrieri.

(viii) International Union of Radio Science Commission F Symposium on Radio and Nonionized Media at La Londe-les-Maures, France, Sept. 11-15, 1989, "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes-Full Wave Approach," with R. Kubik.

(7.2) Papers Submitted to Journal Editors for Review

(i) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada.

(ii) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada.

(iii) "Physical Models of Nonspecular Scattering in Irregular Stratified Media," Proceedings of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory.

(7.2) continued

(iv) "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik, Proceedings of the International Union of Radio Science Symposium on Radio Wave Propagation and Remote Sensing, La Londe-les-Maures, France.

(v) "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited paper on Review of Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, Proceedings of the National Science Foundation Workshop on Future Directions in Electromagnetic Research, Boston, Massachusetts.

(vi) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts.

(vii) "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts.

(7.3) Papers Accepted for Publication

(i) "Non Specular Scattering by Irregular Layered Media," Proceedings of the 1988 Scientific Conference on Obscuration and Aerosol Research, in press.

(ii) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. Kubik, Proceedings of the IGARSS "89 Conference on Remote Sensing, July 10-14, 1989, Vancouver, Canada, in press.

(iii) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS "89 Conference on Remote Sensing, July 4-10, 1989, Vancouver, Canada, in press.

(iv) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, in press.

(v) "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces, Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

(i) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M.A. Fitzwater, Journal of the Optical Society of America, A, Vol. 6, pp. 33-43, January, 1989.

(ii) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," with C. M. Herzinger and M. A. Fitzwater, Journal of Geophysical Research - Oceans, Vol. 94, No. C2, pp. 2159-2169, February, 1989.

(7.5) M.S. Thesis Completed During this Reporting Period

(i) "Scattering Cross Section Modulation of a Synthetic Aperture Radar Resolution Cell with Application to SAR Imaging Unified Full Wave Approach," by Robert D. Kubik.

Outline of Research Findings

During the reporting period (1 January 1989 - 30 June 1989), the principal investigator presented three papers at Scientific/Technical meetings (see Item (7.1a)) and eight papers have been accepted for presentation in the next few months (see Item (7.1b)). Seven papers were submitted for publication (see Item (7.2)) and five papers were accepted for publication (see Item (7.3)). Two papers were published (see Item (7.4)) and reprints of these papers have been submitted with this report. The M.S. Thesis by R.D. Kubik was accepted. (see Item (7.5)).

The full wave analytical and computational work on the bistatic vertically and horizontally polarized scattering cross sections for one dimensionally rough perfectly conducting surfaces has been completed. A preprint of the paper, "Conditions for the Coalescence of the Full Wave Solutions for Rough Surfaces EM Scattering with Perturbation and Physical Optics Solutions" has been submitted to the sponsor. In this work, the random rough surface is characterized by a four-dimensional Guassian joint probability density function for the surface heights and slopes at two different points on the surface. All the correlations between the surface heights and slopes at two points on the rough surface are taken into account in this analysis. For the initial illustrative examples considered, the surface height autocorrelation function and its Fourier transform, the surface height spectral density function is assumed to be Gaussian. Surfaces with other spectral density functions will also be considered in subsequent illustrative examples.

In order to compare the full wave results with other analytical results both the corresponding physical optics results (based on the Kirchhoff approximations of the surface fields) as well as Rice's small perturbation results (based on the Rayleigh approximations for the scattered field) are evaluated.

For horizontally polarized waves it is shown that the full wave results reduce to the small perturbation results only when the rough surface mean square slopes are negligibly small ($\sigma_s^2 \leq 0.001$). (The first order perturbation results of Rice

of the analytical solutions are very difficult due to singularities in the coupling coefficients.

The second approach used to account for multiple (two bounce) scattering from rough surfaces is based on an iterative procedure using the full wave integral expressions for the single scattered field. Since the full wave solutions (which account for upward and downward scattering) can also be used to compute the fields near the rough surface, the single scattered field incident upon the rough surface is first computed. It is regarded as the impressed field in the full wave scattering integrals to obtain the multiply (two bounce) scattered field. A geometric optics (stationary phase) approximation of the full wave solutions show that for backscatter at normal incidence, the maximum slope of the rough surface must exceed 45° in order for multiple scattering to occur. However, the full wave expression shows that multiple scatter occurs for more moderate slopes. The intensity of the multiply scattered waves decrease significantly as the maximum slope decreases below 40°. Moreover, it is shown that for surfaces with maximum slopes, in excess of 45°, there exist several (stationary phase) ray paths. For backscatter the ray paths exist in pairs that reinforce each other. However, away from the backscatter direction these stationary phase contributions interfere with each other and the multiply scattered contributions drop sharply at about 10°-15° away from normal. It is also shown that for incident angles greater than 20°, the multiply scattered contributions become small (compared to single scatter) even for the backscatter direction. These results are consistent with experimental observation in controlled laboratory environments. The computation work has been carried out on the NSF supported Super Computer Center at Cornell University. The preliminary results on multiple scatter will be presented at an ARO workshop organized by the contract monitor, Dr. W. L. (Bud) Flood for July 28-29, 1989 at Boston University, Boston Massachusetts.

for horizontally polarized waves, correspond to zero slope). For scattering in the near specular direction, there is general agreement between the full wave physical optics and perturbation results when the Rayleigh roughness parameter $\beta = 4k_o^2 <h^2> < 0.1$ and the mean square slopes $\sigma_s^2 \leq 0.002$. However, the agreeeent is not good in the backscatter direction.

It is also shown that shadowing plays a very important role for scattering near grazing angles even when the mean square slopes are small. The self-shadowing terms (which restrict the local angles of incidence and scatter to less than 90°) have a very significant impact on the results. Thus the physical optics approximations of the shadowing effects are not valid for near grazing angles.

The computer programs for the bistatic cross sections of three dimensionally rough surfaces hav⸱ been generalized in order to evaluate the like and cross polarized scattering cross ·sections· for any scatter direction in the half space above the rough surface and not just in the plane of incidence. New graphic programs are being utilized to present this data.

Significant advances have been made on the evaluation of multiply scattered waves from rough surfaces with large mean square slopes ($\sigma_s^2 > 1$). At this time however to make the problem more tractable, only one dimensionally rough surfaces are considered.

Using a more formal approach, the generalized telegraphists' equations which are integro (over the wave number spectra) differential (with respect to the space variable) equations, are converted into a matrix differential equation for the scattered wave amplitudes by discretizing the wave number spectra. Analytical solutions for the modified scattered wave amplitudes are derived from these matrix differential equations. These solutions account for multiple scattering in a unified self-consistent manner. However, numerical evaluations

Work on the evaluation of the scatter cross sections for rough surfaces with non-Gaussian surface height statistics is nearing completion. The complete 4x4 Mueller (Phase) matrix elements that characterize E-M scattering from rough surfaces can be computed. These computations can be used in conjunction with recent polimetric techniques for image enhancement and detection purposes.

PROGRESS REPORT #5

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 July 1989 - 31 December 1989

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough
Terrain and Sea-A Unified Full Wave
Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: __Ezekiel Bahar__

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP
DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator
Graduate Research Assistants

Ezekiel Bahar
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(7.1b)   Papers Accepted/Submitted for Presentation at Technical
         Meetings

(i)   International Union of Radio Science (URSI) Meeting,
University of Colorado, Boulder, Colorado,
January 3-5, 1990, Electromagnetic Scattering and
Depolarization Across Rough Surfaces - Full Wave Solution, with
G. Huang.

(ii)   International Union of Radio Science (URSI, Commission F)
Conference on Signature Problems in Microwave Remote Sensing of
the Surface of the Earth, Hyannis, Massachusetts, May
16-18, 1990, "Remote Sensing of the Sea Surface Contaminated by
Monomolecular Oil Slick: Full Wave Approach, with R. Kubik.

(iii)   1990 International Geoscience and Remote Sensing Symposium
(IGARSS '90) Symposium on Remote Sensing Science for the
Nineties, University of Maryland, College Park,
Maryland, May 20-24, 1990, Statistical Characterization of
Random Rough Surfaces Using the Tilt Modulation of the
Backscatter Radar Cross Sections: Full Wave Approach, with Y. F.
Li.

(iv)   IEEE AP-S International Symposium and URSI Radio Science
Meeting, May 7-11, 1990, Dallas, Texas, "Full Wave
Multiple Scattering From Rough Surfaces", with M. El-Shenawee.

(v)   XXIIIrd General Assembly of the International Union of Radio
Science, Prague, Czechoslovakia, August 28 - September 5,
1990, "Radiowave Propagation Over Terrain Characterized by a
Broad Range of Roughness Scales and Varying Electromagnetic
Parameters", Invited Paper.

(vi)   International Union of Radio Science Symposium on
Scattering From Random Media (Joint Session B/F), Prague,
Czechoslovakia, August 28 - September 5, 1990, "Like and
Cross Polarized Backscatter Enhancement and Antispecular
Transmission from Finitely Conducting Two Dimensionally Rough
Surfaces".

(7.2)   Papers Submitted to Journal Editors for Review

(i)   Conditions for the Coalescence of the Full Wave Solutions
for Rough Surface EM Scattering with Perturbation and Physical
Optics Solutions, submitted for review.

(ii)   Unified and Two Scale Full Wave Solutions to Interpret
Apollo Lunar Surface Data with M. Haugland, submitted for review.

(iii)   Tilt Modulation of Synthetic Aperture Radar Backscatter
Cross Sections: Unified Full Wave Approach with R. Kubik,
submitted for review.

(iv)   Computer Simulation of Synthetic Aperture Polarimetric Images
- Unified Full Wave Approach with R. Kubik, submitted for review.

(v) "Electromagnetic Scattering and Depolarization Across Rough Surfaces - Full Wave Solutions" with G. Huang, submitted for review.

(vi) "Scattering Cross Sections for Composite Models of Non-Gaussian Rough Surfaces: Unified Full Wave Approach" with Y. F. Li, submitted for review.

(vii) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Models of Non-Gaussian Rough Surfaces: Unified Full Wave Approach" with Y. F. Li, submitted for review.

(viii) "Statistics for Identifying Contaminated Rough Surfaces by Polarized IR Scattering: Full Wave Approach" with S. M. Haugland and A. H. Carrieri, submitted for review.

(ix) "Full Wave Multiple Scattering From Rough Surfaces" with M. El-Shenawee, submitted for review.

(7.3) Papers Accepted for Publication

(i) "Physical Models of Nonspecular Scattering in Irregular Stratified Media", <u>Proceedings of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory</u>, Stockholm, Sweden, August 14-17, 1989, in press.

(ii) Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach, with R. Kubik, <u>Proceedings of the International Union of Radio Science Symposium on Radio Wave Propagation and Remote Sensing</u>, La Londe-les-Maures, France, September 11-15, 1989, in press.

(iii) Electromagnetic Wave Scattering by Randomly Rough Boundaries, Invited Paper - Review on Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, <u>Proceedings of the National Science Foundation Workshop on Future Direction in Electromagnetic Research</u>, Boston, Massachusetts, July 29, 1989, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

(i) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media", with M. A. Fitzwater, <u>IEEE Transactions on Antennas and Propagation</u>, Vol. AP-S 37, No. 12, pp. 1609-1616, December, 1989.

(ii) "Non Specular Scattering by Irregular Layered Media", <u>Proceedings 1988 Scientific Conference on Obscuration and Aerosol Research</u>, Aberdeen, Maryland, CRDEC-SP pp. 1-8, 1989.

(iii)   "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach", with R. Kubik, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada, IEEE #89CH2768-O, Vol. 3, pp. 1292-1295, July 10-14, 1989.

(iv)   "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach", with M. Haugland, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada, IEEE #89CH2768-O, Vol. 3, pp. 1296-1299, July 4-10, 1989.

(v)   Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths, Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, pp. 146-147, July, 1989.

(vi)   Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces, Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, pp. 398-399, July, 1989.

(7.5)   M.S. Thesis Completed During this Reporting Period

(i)   "Scattering and Depolarization of Electromagnetic Waves from Random Rough Surfaces with Non-Gaussian Statistics - Full Wave Solution by Yan-Feng Li.

Brief Outline of Research Findings

During the reporting period (1 June 1989 - 31 December 1989), the principal investigator presented eight papers at Scientific/Technical meetings (see Item # (7.1a)) and six papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item # (7.1b)). Nine papers were submitted to journal editors for review (see Item # (7.2)) and three were accepted for publication (see Item # (7.3)). Six papers were published in journals and conference proceedings (see Item # (7.4)) and reprints of these papers have been submitted with this report. The M.S. thesis of Yan-Feng Li was accepted (see Item # (7.5) copy enclosed).

On July 28, 1989, the principal investigator attended an ARO/RADC sponsored workshop on "Enhanced Backscatter from Random Rough Surfaces" at Boston University, Boston, Massachusetts. The workshop was organized by the ARO contract monitor, Dr. Walter (Bud) Flood. At the workshop, an oral progress report was presented. Emphasis was given to the full-wave multiple scatter results during the principal investigator's presentation (see Item # (7.1b)(iv)). A preprint of this work was also submitted to the project monitor. In this work, the effects of varying the following parameters are investigated: angle of incidence, mean square slope, mean square height, correlation length, polarization and the complex permittivity of the scattering medium. It is shown that interference between different multiply

scattered fields can be responsible for the rapid fluctuation of the backscattered intensity (with view angle) for normal incidence. However, for oblique incidence (0 > 20) the multiple scattered intensity is smaller than the single scattered intensity. Thus the enhanced backscatter observed at oblique incidence is primarily due to the single scatter contributions. For these cases, there are no fluctuations of the backscattered field intensity (with view angle). The computation of the full-wave single and multiple scattered fields were carried out on the NSF supported super computer facility at Cornell University.

The evaluation of the scattering cross section for rough surfaces with non-Gaussian characteristics has been completed. Both real and synthetic aperture radars are considered. Methods to distinguish between surfaces with different statistical characterizations are also evaluated (see Item # (7.2)(vi) and (vii) and Thesis Item (7.5)).

Full wave analytical expressions have been derived for the scattering and depolarization of electromagnetic waves across a rough interface. Preliminary work has shown that as the surface roughness increases (large mean square slopes and small correlation lengths) the transmitted wave contains a strong non-specular component akin to the enhanced backscatterd intensity from very rough conducting surfaces.

PROGRESS REPORT #6

TWENTY COPIES REQUIRED

1.   ARO PROPOSAL NUMBER: 25130-GS

2.   PERIOD COVERED BY REPORT: 1 January 1990 - 30 June 1990

3.   TITLE OF PROPOSAL: Scattering and Depolarization by Rough
                          Terrain and Sea-A Unified Full Wave
                          Approach

4.   CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5.   NAME OF INSTITUTION: University of Nebraska

6.   AUTHORS OF REPORT: <u>   Ezekiel Bahar   </u>

7.   LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP
     DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

          See Attached List

8.   SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED
     DURING THIS REPORTING PERIOD:

          Professor Ezekiel Bahar
          Graduate Research Assistants

Ezekiel Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NE 68588-0511

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings

(i) International Union of Radio Science (URSI) Meeting, <u>University of Colorado, Boulder, CO</u> Jan. 3-5, 1990, Electromagnetic Scattering and Depolarization Across Rough Surfaces--Full Wave Solution with G. Huang.

(ii) First Los Alamos Symposium on Ultra-Wideband Radar, <u>Los Alamos National Laboratory,</u> Mar. 5-8, 1990, "Rough Surface Scattering Cross Sections for Ultra-Wideband Radars."

(iii) IEEE AP-S International Symposium and URSI Radio Science Meeting, May 7-11, 1990, <u>Dallas, Texas,</u> "Full Wave Multiple Scattering from Rough Surfaces with M. El-Shenawee.

(iv) International Union of Radio Science (URSI, Commission F) Conference on Signature Problems in Microwave Remote Sensing of the Surface of the Earth, <u>Hyannis, MA,</u> May 16-18, 1990, "Remote Sensing of the Sea Surface Contaminated by Monomolecular Oil Slick: Full Wave Approach," with R. Kubik.

(v) 1990 International Geoscience and Remote Sensing Symposium (IGARSS '90) Symposium on Remote Sensing Science for the Nineties, <u>University of Maryland, College Park, MD,</u> May 20-24, 1990, "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscatter Radar Cross Sections: Full Wave Approach, with Y.F. Li.

(vi) 1990 CRDEC Scientific Conference on Obscuration and Aerosol Research, <u>Aberdeen, MD,</u> June 25-28, 1990, "Multiple Scattering of Electromagnetic Waves from Coated Rough Surfaces," with Mark Haugland.

(7.1b) Papers Accepted for Presentation at Technical Meetings

(i) XXIIIrd General Assembly of the International Union of Radio Science, <u>Prague, Czecho-slovakia,</u> Aug. 28 - Sep. 5, 1990, "Radiowave Propagation Over Terrain Characterized by a Broad Range of Roughness Scales and Varying Electromagnetic Parameters," Invited Paper

(ii) International Union of Radio Science Symposium on Scattering from Random Media (Joint Session B/F), <u>Prague, Czechoslovakia,</u> Aug. 28 - Sep. 5, 1990, "Like and Cross Polarized Backscatter Enhancement and Antispecular Transmission from Finitely Conducting Two Dimensionally Rough Surfaces."

(iii) Advisory Group for Aerospace Research and Development Fall 1990, Electromagnetic Wave Propagation Panel Symposium on Use or Reduction of Propagation and Noise Effects in Distributed Military Systems, <u>Rethymno, Crete, Greece,</u> Oct.15-19, 1990, "Utilization or Reduction of the Effects of Sea Clutter for Real and Synthetic Aperture Polarimetric Radars."

(iv) The Fourth Biennial IEEE Conference on Electromagnetic Field Computation, Toronto, Canada, Oct. 22-24, 1990, "Use of Supercomputers to Evalute Singly and Multiply Scattered Electromagnetic Fields from Rough Surfaces," with M. El-Shenawee.

(v) 1990 U.S. Army Chemical Research Development and Engineering Center Scientific Conference on Chemical Defense Research, <u>Aberdeen, MD,</u> Nov 13-16, 1990, "Computation of Mueller Matrix Elements for Irregular Stratified Media - Full Wave Approach," with Mark Haugland.

(7.2) Papers Submitted to Journal Editors for Review

(i) "Acoustic Scattering by Two-Dimensionally Rough Interfaces Between Dissipative Acoustic Media - Full Wave, Physical Acoustics and Perturbation Solutions," submitted for review.

(ii) "Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions," submitted for review. Revised.

(iii) "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscattered Radar Cross Sections: Full Wave Approach," with Yan-Feng Li, submitted for review.

(7.3) Papers Accepted for Publication

  (i) "Full Wave Solutions for the Scattering of Acoustic Waves Excited by Arbitrary Source Distributions in Irregular Layered Media," Wave Motion, in press.

  (ii) "Full Wave Multiple Scattering From Rough Surfaces" with M. El-Shenawee, Proceedings of the IEEE AP-S International Symposium and URSI Radio Science Meeting, Vol. IV, pp. 1548-1551, May, 1990.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

  (i) "Scattering of Acoustic Waves in Irregular Layered Media - Full Wave Solutions," Wave Motion, Vol. 12, pp. 53-65, Jan. 1990.

  (ii) "Physical Models of Nonspecular Scattering in Irregular Stratified Media," Proceedings of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory, Stockholm, Sweden, pp. 503-505, Aug. 14-17, 1989.

(iii) "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. Kubik, Proceedings of the International Union of Radio Science Symposium on Radio Wave Propagation and Remote Sensing, La Londe-les-Maures, France, pp. 7.1.1 - 7.1.4. Sep. 11-15, 1989.

  (iv) "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited Paper - Review on Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, Proceedings of the National Science Foundation Workshop on Future Direction in Electromagnetic Research, Boston, MA, pp. 311-314, July 29, 1989.

  (v) "Full Wave Multiple Scattering From Rough Surfaces" with M. El-Shenawee, Proceedings of the IEEE AP-S International Symposium and URSI Radio Science Meeting, Vol. IV, pp. 1548-1551, May, 1990.

  (vi) "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscattered Radar Cross Sections: Full Wave Approach," with Yan-Feng Li, Proceedings of the International Geoscience and Remote Sensing Symposium, Vol. II, pp. 1401-1403, May, 1990.

(7.5) M.S. Thesis Completed During This Reporting Period

  (i) "Tranmission Scattering and Depolarization of Electromagnetic Waves Across Rough Interfaces, Full Wave Approach," by Guorong Huang.

Brief Outline of Research Findings

During the reporting period (1 January 1990 - 30 June 1990), the principal investigator presented six (6) papers at Scientific/Technical Meetings (see Item #(7.1a)) and five (5) papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item #(7.1b)). Three (3) papers were submitted to Journal Editors for Review (see Item #(7.2)) and two (2) were accepted for publication (see Item #(7.3)). Six (6) papers were published in journals and conference proceedings (see Item #(7.4)) and reprints of these papers have been submitted with this report. The M.S. Thesis of Guorong Huang was accepted (see Item #(7.5), copy enclosed).

At the URSI Meeting in Boulder (7.1a)(i)), the full wave solutions were presented for the scattered and depolarized waves that propagate across rough interfaces between two media. For surfaces with large mean square slopes and small correlation lengths, the transmitted fields exhibit a very strong non-specular component that is physically analogous to the enhanced backscattered intensity observed from very rough surfaces. This work was also presented as an M.S. Thesis by Guorong Haung in May 1990 ((7.5)(i), copy enclosed). The paper presented at the Los Alamos Symposium on Ultra Wideband Radar (7.1a)(ii) exploits the fact that the full wave approach can be applied to composite rough surfaces without resorting to an artificial decomposition of the surface into surfaces with small and large roughness scales. At the IEEE AP-S/URSI Meeting ((7.1a)(iii)), the singly and multiply scattered fields from one dimensional surfaces with very large slopes were presented. It is shown that the multiply (two bounce) scattered fields were primarily forward (near specularly) directed while the singly scattered fields are primarily backscattered. Thus for normal incidence the backscattered fields consist of several interfering field components.

This work is published in the Proceedings of the Symposium ((7.3)(ii), (7.4)(v)). Work is presently being conducted to extend these results to two dimensionally rough surfaces. At the URSI Commission F Meeting ((7.1a),(iv)), the results of our investigations of the radar cross sections for sea surface coated by oil slicks were presented. At the IGARSS Meeting ((7.1a),(v)), it was shown how the predictions based on the tilt modulation of the backscattered radar cross sections can be used to determine the statistical characterization of Random Rough Surfaces. This work is also published in the Conference Proceedings ((7.2),(iii)). The paper presented at the CRDEC Conference ((7.1a),(vi)), deals with multiple scattering from coated rough surfaces.

It is shown in a recent paper submitted for publication ((7.2),(ii)), that the fields scattered by slightly rough surfaces cannot be characterized solely on the basis of the mean square heights and slopes of the surfaces. When the small heights and slopes are bounded, the full wave solutions are in agreement with Rice's first order small perturbation solution. However, if the heights and slopes are characterized by an unbounded joint (four dimensional) Gaussian probability density function, specular point scattering dominates the solution (in agreement with Beckmann's results), except near grazing angles where the full wave solutions are shown to vanish. It is also shown how Rice's first order perturbation solution can be related to the full wave single scatter solution through a phase modification and a coordinate transformation.

The topics of the six papers that were published during this reporting period ((7.4), reprints enclosed), were discussed in earlier reports.
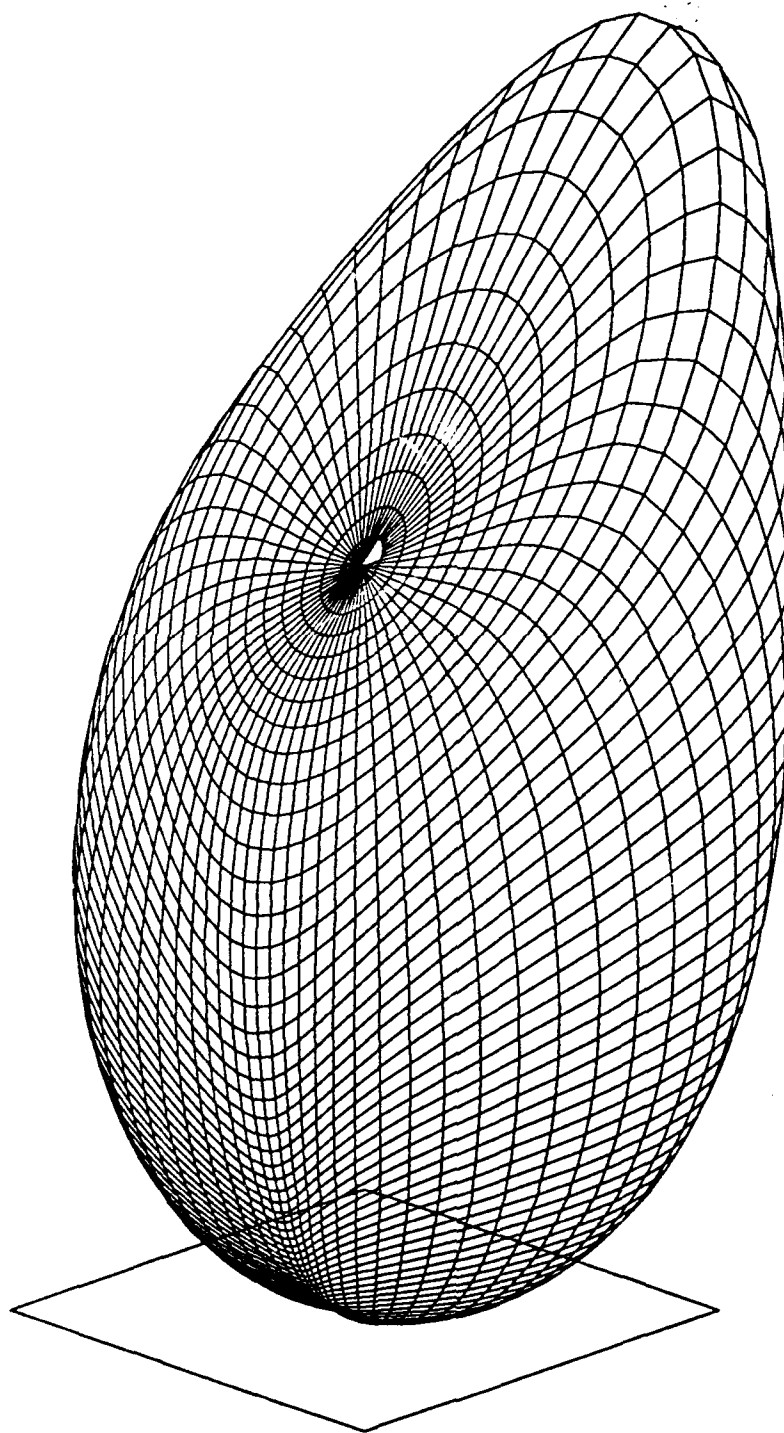
9. ILLUSTRATIONS

Fig. (9.1) Bistatic cross sections $\langle\sigma^{VV}\rangle + \langle\sigma^{HV}\rangle$ for a vertically polarized wave incident at $\theta_0^i = 20°$.
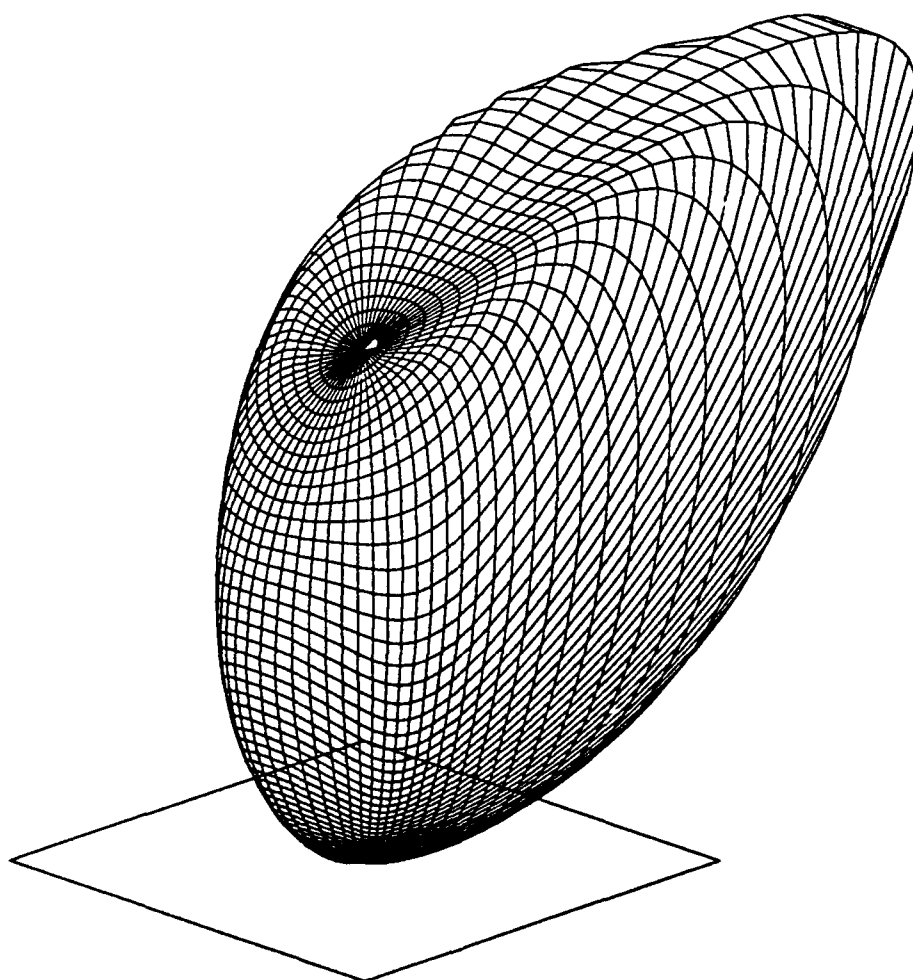
Fig. (9.2) Bistatic cross sections $\langle\sigma^{HH}\rangle + \langle\sigma^{VH}\rangle$ for a horizontally polarized wave incident at $\theta_o^i = 50^o$.